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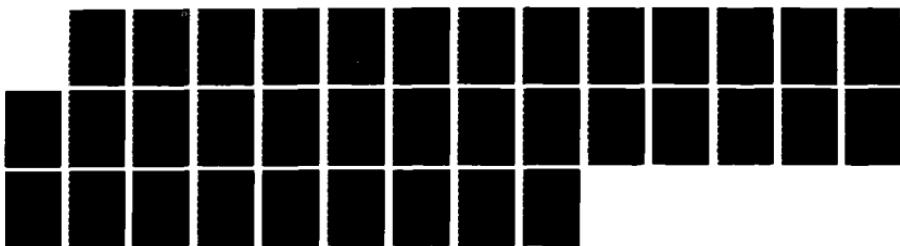
PARALLEL CURRENT EFFECTS ON AURORAL E-REGION PLASMA
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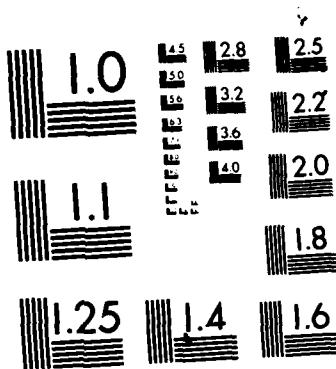
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Parallel Current Effects on Auroral E-Region Plasma Instabilities

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CONTENTS

I.	INTRODUCTION	1
II.	THEORY	3
III.	DISCUSSION	8
ACKNOWLEDGMENT		13
REFERENCES		13

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PARALLEL CURRENT EFFECTS ON AURORAL E-REGION PLASMA INSTABILITIES

I. INTRODUCTION

It is generally agreed that the electrojet current in the auroral E-region is responsible for generation of the plasma density irregularities which have been detected by several experimental techniques [Fejer and Kelley, 1980]. The coherent radar backscatter returns at 50 MHz (which are caused by the presence of 3-meter size irregularities) have yielded a large amount of data on the features of these irregularities. These irregularities have been classified into three types based upon the doppler spectra of the radar returns. The type I irregularities display a narrow spectral peak around the ion sound velocity and are believed to be caused by the Farley-Buneman instability; this instability can occur when the electron Hall drift velocity exceeds the ion-sound velocity [Balsley and Ecklund, 1972]. The type II irregularities are believed to be a result of a nonlinear cascade by large scalesize irregularities that are generated by the gradient-drift instability mechanism (the Hall current acting upon a transverse gradient) and can be excited for electron drift speeds less than the ion sound velocity. The type II spectra are relatively broad around the $\mathbf{E} \times \mathbf{B}$ electron Hall drift velocity [Greenwald, 1974; Greenwald et al., 1975]. Both the type I and II spectra are caused by modes that are excited in the direction transverse to the ambient magnetic field (as the driving electric field is also perpendicular to the magnetic field).

However, there are many instances when the irregularity observations are found to show departures from the above patterns. There have been

observations of type I irregularities at a time when the electron Hall drift was subcritical, i.e., less than the ion sound speed, C_s [Siren et al., 1977]. There is now evidence of a new type of irregularity, termed type III, which displays even a narrower doppler spectra than the type I, but peaked around velocities less than the ion sound speed and not as highly field-aligned as the types I and II, i.e., has a finite structure along the magnetic field [Haldoupis et al., 1985; Fejer et al., 1984a; Greenwald et al., 1975]. A field-aligned current-driven electrostatic ion-cyclotron instability has been invoked to interpret these irregularities [D'Angelo, 1973; Chaturvedi, 1976; Ogawa et al., 1981; Fejer et al., 1984b; Bering, 1984; Haldoupis et al., 1985; Providakes et al., 1985; Satyanarayana et al., 1985]. However, the theory for the ion-cyclotron instability can only be justified in the upper E-region (altitudes ≥ 130 km) where ions are magnetized ($v_{in} < \Omega_i$, where v_{in} is the ion-neutral collision frequency and Ω_i is the ion gyrofrequency), and care must be exercised while using the ion-cyclotron instability mechanism at lower altitudes where the ions are collisional, i.e., $v_{in} \gtrsim \Omega_i$ (~ 100 -120 km altitudes).

In this report, we consider the plasma instability processes occurring at E-region altitudes, where ions are collisional, and include the effects of an equilibrium parallel current [Akasofu, 1984]. We find that the inclusion of a parallel electron drift makes possible the excitation of the Farley-Buneman (F-B) instability for electron Hall drifts lower than the ion-sound speed, and can result in the excitation of obliquely propagating F-B and ion-sound modes. In this regard, we mention that auroral irregularities have been observed in the regions of downward Birkeland currents (that are carried by the thermal electrons) [Tsunoda et al., 1976; McDiarmid and McNamara, 1978], and, in the vicinity of Harang Discontinuity [Sofko et al., 1985]. In this work, we have not considered any nonlocal

effects for these modes [Kaw, 1972; Moorcroft, 1984; St.-Maurice, 1985]. In the following, we first present a brief outline of the theoretical approach and then discuss the results for the auroral E-region situation.

II. THEORY

A general dispersion relation describing the auroral E-region modes has been given in many places; we consider the one derived by Fejer et al. [1984b] using the two-fluid equations. The use of fluid equations is valid for wavelengths greater than the ion-mean-free path (\gtrsim a meter) [Schmidt and Gary, 1973]. The coordinate system used here has the z-axis aligned with the Earth's magnetic field, $B_0 z$. An equilibrium transverse electric field, E_{0x} , results in the electron Hall drift, v_{0y} , along the y-axis (East-West direction). An equilibrium parallel current, J_{0z} , (carried by thermal electrons with a drift velocity, v_{0z}) is assumed to be present. The ions are assumed collisional ($v_{in} \gtrsim \Omega_i$) and the electrons are magnetized ($v_{en} \ll \Omega_e$), where v_{in} and $\Omega_\alpha (= e_\alpha B_0 / m_\alpha c)$ are, respectively, the particle collision frequency with neutrals and the gyrofrequency, and m_α is the particle mass. For obliquely propagating modes [$\sim \exp(ik_y y + ik_z z - i\omega t)$], the dispersion relation is

$$(\omega - \underline{k} \cdot \underline{v}_0)(v_{in} - i\omega) + \{\omega[\Omega_i^2 + (v_{in} - i\omega)^2] + ik^2 C_s^2 (v_{in} - i\omega)\} \frac{\Psi}{v_{in}} = 0 \quad (1)$$

where

$$\Psi = \frac{v_e v_{in}}{\Omega_e \Omega_i} \left(1 + \frac{\Omega_e^2}{v_e^2} \frac{k_z^2}{k^2} \right); C_s^2 = \frac{(T_e + T_i)}{m_i} \quad (2)$$

In the above, recombination damping is neglected (as it is important only for the long wavelength modes, whereas we are interested in the 3 meter irregularities) and electron inertia is ignored. The symbols used have

their standard meanings: $\underline{k} = k_y \hat{y} + k_z \hat{z}$ is the modal wavenumber and ω the complex frequency, v_0 is the equilibrium electron drift velocity with a Hall component (v_{oy}) and a parallel component (v_{oz}), and T_α is the temperature expressed in energy units.

For collisional altitudes ($v_{in} > \Omega_i$), we may rewrite eq. (1) as

$$(\omega - \underline{k} \cdot \underline{v}_0) + [\omega v_{in} - i(\omega^2 - k^2 c_s^2)] \frac{\Psi}{v_{in}} = 0 \quad (3)$$

This dispersion relation can be solved to yield the Farley-Buneman instability and the ion-acoustic instability, respectively, in the approximations $|\omega| < v_{in}$ and $|\omega| > v_{in}$. We now present the analytical expressions for the two cases, and, will present some numerical results appropriate for the auroral electrojet in the next section.

A. Modified Farley-Buneman Instability

It is straightforward to obtain the usual result of the Farley-Buneman instability from the above (i.e., $k_z = 0$). One finds that [Fejer et al. 1984b] the real frequency and the growth rate are given as ($\omega = \omega_r + i\gamma$, $|\gamma| < \omega_r$)

$$\omega_r = \frac{1}{(1 + \Psi)} k_y v_{oy} \quad (4a)$$

and

$$\gamma \approx \frac{\Psi}{v_{in}(1 + \Psi)} (\omega_r^2 - k_y^2 c_s^2) \quad (4b)$$

where $\Psi = v_e v_{in} / \Omega_e \Omega_i$. Instability occurs when $v_{oy} > (1 + \Psi) c_s$.

For $k_z \neq 0$, we can write (3) as

$$\omega = \frac{\underline{k} \cdot \underline{v}_0}{(1 + \Psi)} + i \frac{(\omega^2 - k^2 c_s^2) \Psi}{v_{in}(1 + \Psi)} \quad (5)$$

where Ψ has been defined in (2). From (5), we can write approximate expressions for real frequency and the growth rate of the modes as follows ($\omega = \omega_r + i\gamma$, $|\gamma| < \omega_r$)

$$\omega_r = \frac{1}{(1 + \Psi)} (k_y v_{oy} + k_z v_{oz}) \quad (6a)$$

$$\gamma = \frac{\Psi}{v_{in}(1 + \Psi)} (\omega_r^2 - k^2 c_s^2) \quad (6b)$$

The new instability condition is given by

$$v_{oy} + \frac{k_z}{k_y} v_{oz} > \frac{k}{k_y} (1 + \Psi) c_s \quad (7)$$

For a parameter domain such that $(k_z/k)(\Omega_e/v_e) \gg 1$ [and, $(\Omega_e/v_e)(v_{in}/\Omega_i)(k_z^2/k^2) > 1$], it may be readily verified that the growth rate (and the real frequency) in (6) maximize for $(k_z/k) \sim 2(v_{oy}/v_{oz})$. Note that this implies that the modes are not too highly field-aligned ($k_z/k \gg v_e/\Omega_e$). In the general case, the criteria determining the optimum growth rate (and the real frequency) are somewhat complex, and we have not attempted to present them here. For $k_z = 0$, (7) yields the usual instability criterion ($v_{oy} > (1 + \Psi)c_s$) of the Farley-Buneman instability. For $k_z \neq 0$ and $v_{oz} = 0$, we recover the result that the inclusion of parallel wavelengths increases the threshold value of electron drift required for the excitation ($v_{oy} > (1 + \Psi)c_s$) [Ossakow et al., 1975]. Since, $\Psi \gtrsim 1$ for the parameter domain of our interest, the requirement, $v_{oy} > \Psi c_s$, may be difficult to satisfy in actual situations. The drift velocity condition for instability in this case may be expressed as

$$v_{oy} > \frac{k}{k_y} (1 + \Psi) c_s - \frac{k_z}{k_y} v_{oz}$$

It is clear from (7) that for sufficiently large values of v_{0z} , an obliquely propagating mode may still be excited and, further, the instability criterion may be met for $v_{oy} < C_s$.

B. Ion-Acoustic Instability

The ion-acoustic wave excitation by the Hall current in auroral electrojet has been discussed by Kaw [1973]. Here we include the effects of a parallel current on this mode. For $v_{in} < |\omega|$, we find from (3) that the dispersion relation for obliquely propagating ion sound waves is

$$\omega(\omega + i\bar{v}_{in}) - k^2 C_s^2 = - i \frac{m_e}{m_i} \frac{k^2}{k_z^2} v_e (\omega - \frac{k \cdot v_0}{\omega_e}) / \left(1 + \frac{v_e^2}{\omega_e^2} \frac{k^2}{k_z^2} \right) \quad (8)$$

where $\bar{v}_{in} = v_{in} + (\pi/2)^{1/2} (\omega^4 / |k| k^2 v_i^3) \exp(-\omega^2 / 2k^2 v_i^2)$, and we have included the ion-Landau damping effects for completeness. We can write the real frequency and growth rate for these modes from (8) as ($\omega = \omega_r + i\gamma$, $|\gamma| < \omega_r$),

$$\omega_r \approx k C_s \quad (9a)$$

$$\gamma \approx - \frac{1}{2} \bar{v}_{in} - \frac{1}{2} \frac{m_e}{m_i} \frac{k^2}{k_z^2} v_e \left(1 - \frac{k \cdot v_0}{\omega_r} \right) / \left(1 + \frac{v_e^2}{\omega_e^2} \frac{k^2}{k_z^2} \right) \quad (9b)$$

Physically, the current-driven ion-acoustic instability is related to the parallel dissipative motion of electrons. In the absence of equilibrium currents ($v_0 = 0$), the second term in (9b) represents the damping of the mode by the collisional parallel electron motion (v_e) that inhibits them from being redistributed in wave potential in Boltzmann-like distribution [$n_e \sim n_0 \exp(-e\phi/T_e)$], thereby making the density-potential relationship

complex. In the presence of equilibrium currents (v_0), the electrons "see" the waves at a Doppler-shifted frequency ($\omega - \underline{k} \cdot \underline{v}_0$); for equilibrium drift velocity larger than the wave phase velocity in the drift direction ($\omega < \underline{k} \cdot \underline{v}_0$), the wave energy in the drift frame becomes negative. Thus, the dissipation of the negative energy wave leads to a wave growth. The second term in the denominator in the growth term in (9b) results from the transverse collisional motion of electrons, and has an effect of reducing the growth rate. For the case of Hall currents, $v_0 = v_{oy} \hat{e}_y$, we recover from (9b), the instability discussed by Kaw [1973]. For a parallel current, $v_0 = v_{oz} \hat{e}_z$, a collisional ion-acoustic instability is obtained. In general, the instability criterion may be written down as,

$$\frac{k_y}{k} \frac{v_{oy}}{C_s} + \frac{k_z}{k} \frac{v_{oz}}{C_s} > 1 + \frac{\bar{v}_{in}}{v_e} \frac{k_z^2}{k^2} \frac{m_i}{m_e} \left(1 + \frac{v_e^2}{\Omega_e^2} \frac{k_y^2}{k_z^2} \right) \quad (10)$$

where as noted before, \bar{v}_{in} includes the ion-Landau damping effects. In the upper auroral E-region where v_{in} is sufficiently small (so that $v_{in} < \omega_r \sim kC_s$), we find that a parallel current (in possible conjunction with the Hall current) may drive an oblique ion-sound mode unstable. This result may have relevance to the observations of non-field-aligned auroral irregularities [Haldoupis et al., 1985]. We also mention that, as noted by Kaw [1973], the time-dependence of the ion sound wave frequency due to the evolution of electron temperature (T_e) in a collisional medium is not a problem here. In the partially ionized auroral E-region, T_e reaches a steady state value in an energy relaxation time $(m_e v_e / m_i)^{-1}$ after which it stays constant, the neutrals providing the sink of energy. Further, the experimental observations of enhanced electron temperatures (which make $T_e/T_i > 1$) [Schlegel and St.-Maurice, 1981] suggest a possible excitation of ion-sound waves, as the thresholds for excitation at $T_e/T_i > 1$ are lower

than the case with $T_e = T_i$ [Kindel and Kennel, 1971].

III. DISCUSSION

In the above, we have included the effects of a parallel equilibrium current (carried by drifting electrons) on the excitation of the Farley-Buneman and ion acoustic instabilities in the auroral electrojet. The presence of a parallel current modifies the dispersion equation for these modes, and makes possible the excitation of obliquely propagating modified Farley-Buneman and ion acoustic modes for sub-critical levels of electron Hall drift ($v_{oy} \lesssim C_s$). We now present some numerical estimates for the threshold requirements on the parallel currents for the excitation of these modes in the auroral E-region.

We numerically solve (3) for parameters appropriate to the auroral electrojet region. For an altitude of 105 km we consider the following typical parameters: $v_e \approx 3.5 \times 10^4 \text{ sec}^{-1}$, $v_{in} \approx 2.5 \times 10^3 \text{ sec}^{-1}$, $\Omega_e \approx 8.8 \times 10^6 \text{ sec}^{-1}$, $\Omega_i \approx 1.8 \times 10^2 \text{ sec}^{-1}$, and $C_s = 350 \text{ m/sec}$. For 3 m wavelength waves we note that $v_{in}/kC_s \approx 3.5$. In Fig. 1 we plot the real frequency ω_r/kC_s vs k_z/k_y (Fig. 1a) and the growth rate γ/kC_s vs k_z/k_y (Fig. 1b) for $v_{oy}/C_s = 1.0$ and $v_{oz}/C_s = 0$ (A), 25 (B), 50 (C) and 75 (D). We note the following. First in the absence of a parallel current ($v_{oz} = 0$), the turn-on criterion for instability is $v_{oy} > (1 + \hat{\psi})C_s$. Since we have taken $v_{oy}/C_s = 1$ we expect the Farley-Buneman mode to be stable and this is clearly evident from curve A in Fig. 1b (i.e., $\gamma < 0$). Second, for finite values of v_{oz} and k_z unstable modes can be excited (e.g., see curves C and D of Fig. 1b). The band of unstable modes corresponds to modes with $\omega_r > kC_s$ (e.g., see curves C and D of Fig. 1a). Third, for sufficiently large values of k_z/k_y (for our parameters $k_z/k_y > 0.02$), the unstable modes become damped (i.e., $\gamma < 0$). This is because $\omega_r \approx (k_z/k_y)^{-1}$ for large k_z/k_y (i.e., $k_z/k_y > v_e/\Omega_e$); as k_z/k_y increases, ω_r decreases and

eventually $\omega_r < kC_s$ so that $\gamma < 0$. And fourth, increasing values of v_{oz}/C_s lead to enhanced growth rates and a broader range of instability in k_z/k_y . In Fig. (1c), we have plotted the critical Hall drift required for the excitation of the instability in presence of v_{oz} and k_z . It can be readily seen that for sufficiently large value of v_{oz} , the instability may occur for $v_{oy}/C_s < 1$ (for oblique modes).

At somewhat higher altitudes in the E region, the ion-neutral collision frequency decreases so that $v_{in} < \omega_r$. For example at ~ 115 km we consider the following parameters: $v_e = 5.3 \times 10^3 \text{ sec}^{-1}$, $v_{in} = 3.6 \times 10^2 \text{ sec}^{-1}$, $\Omega_e = 8.8 \times 10^6 \text{ sec}^{-1}$, $\Omega_i = 1.8 \times 10^2 \text{ sec}^{-1}$, and $C_s = 350 \text{ m/sec}$. For 3 m wavelength modes, we note that $v_{in}/kC_s = 0.5 < 1$, and ion acoustic waves may be excited. In Fig. 2 we plot the real frequency ω_r/kC_s vs. k_z/k_y (Fig. 2a) and the growth rate γ/kC_s vs. k_z/k_y (Fig. 2b) for the above parameters with $v_{oy}/C_s = 1.0$ and $v_{oz}/C_s = 0$ (A), 25 (B), 50 (C), and 75 (D). The important features are the following. First, as in Fig. 1, for $v_{oz} = 0$ there are no unstable modes (curve A of Fig. 2b). As k_z/k_y becomes large we note that $\omega_r \sim kC_s$ and $\gamma \sim -v_{in}/2$ in accordance with (9). Second, for finite values of v_{oz} and k_z unstable modes can be excited (as in Fig. 1). In this case we note that the threshold parallel velocity for instability is lower than in the previous case; for example, for $k_z/k_y = 5.0 \times 10^{-3}$ the threshold velocity is $v_{oz} \approx 17 C_s$ for the parameters used in Fig. 2 while it is $v_{oz} \approx 29 C_s$ for those used in Fig. 1. Third, the unstable waves have maximum growth rates somewhat larger than those shown in Fig. 1, and peak at somewhat lower values of k_z/k_y . And fourth, the most significant difference between Figs. 1 and 2 is the asymptotic behavior of ω_r and γ for large k_z/k_y . In Fig. 1, both ω_r and γ monotonically decrease for large values of k_z/k_y ; however, in Fig. 2, ω_r and γ asymptote to $k_y C_s$ and $-v_{in}/2$, respectively for large k_z/k_y . This difference may have observable consequences with regard to the nonlinear

evolution of these modes. We will discuss this shortly. We mention here that Fejer et al. [1984b] have discussed the properties of the two-stream ion-cyclotron mode in the presence of parallel and cross-field currents at an altitude where $v_{in}/\Omega_i \sim 1$.

We see from the above results that for oblique modes ($k_z \neq 0$), the threshold Hall drift for the excitation of the Farley-Buneman instability is very high. Thus, for the excitation with $v_{oz} = 0$ and $k_z/k \approx .02$, the criterion is $v_{oy} \geq 3.5$ km/sec. Such drift velocities would correspond to transverse electric fields ≥ 175 mV/m, a value that is much larger than the reported (though infrequent) measurements of fields up to 150 mV/m. However, there are also measurements, at times, of large scale parallel currents on the order of tens of $\mu\text{A}/\text{m}^2$ in the high latitude ionosphere [e.g., Bythrow et al., 1984]. These currents close in the E-region [Akasofu, 1984]. Thus, obliquely propagating modes in the E-region would be affected by plasma flows both in the transverse as well as in the parallel direction. For a current $J_{oz} \sim 94 \mu\text{A}/\text{m}^2$ [Bythrow et al, 1984], with $n_0 \sim 10^4 \text{ cm}^{-3}$, the parallel electron drift velocity computed from the expression, $J_{oz} \sim n_0 e v_{oz}$, is $v_{oz} \sim 60$ km/s. One finds from Fig. 1 that, for oblique propagation in the presence of such a parallel drift velocity, the Farley-Buneman instability may still directly generate 3 meter irregularities for the sub-critical electrojet velocities, i.e., $v_{oy} < C_s$, or $E_{o\perp} < 20$ mV/m. The Doppler returns in this case would be peaked around a velocity different from the electron Hall drift. We note that an excitation for the sub-threshold conditions of type I irregularities has been reported [Siren et al., 1977]. Further, for parameters listed above for ~ 105 km. altitude, and for $v_{oz} \sim 100 C_s$ and $k_z/k_y = 0.02$, one finds that the electron Hall drift required for excitation (from (7)) is

$$v_{oy} \geq 2.336 C_s - \frac{k_z}{k_y} C_s$$

$$= 0.336 C_s$$

which gives a required drift speed v_{oy} of only 118 m/s, or a Doppler shift of 39 Hz at 50 MHz, in agreement with the Type III observations of the Univ. of Saskatchewan group. However, we wish to mention here that the large parallel currents are also accompanied by enhancements in the ambient density. Thus, the computation of parallel electron drift velocity from the observed current for the corresponding density (as has been done above), often leads to values of drift speeds that fail to meet the thresholds required for excitation. A possibility, that needs to be experimentally checked, is that these large structured currents cause a structure in the density also, with the regions of low density experiencing the plasma wave excitation. We further note here that it has been suggested that the field aligned current generated ion-sound turbulence may be taken into account by introducing an effective (anomalous) electron collision frequency (v^*), and this large v^* may then be used to explain the excitation of oblique Farley-Buneman instability [Volosevich and Liperovskiy, 1975]. The recent observations of non-field-aligned radar echoes by Haldoupis et al. [1986] can be explained by this theory if $v_e^* = 300 v_e$. However, the present theories of plasma turbulence seem unable to account for such a large anomalous enhancement of v_e .

We have noted earlier that the ion-acoustic instability is likely to occur at upper E-region altitudes, where the ion-neutral collision frequency is smaller than the wave frequency. The electrojet current (the electron Hall drift) is maximum at ~ 105-110 km altitudes, and decreases upwards. Thus, ion sound wave excitation may be primarily caused by the field-aligned currents, with possible contributions from the electrojet. For $k_z/k_y \sim .01$ and $v_{in}/v_e \sim 10$, we find from Fig. 2 that a transverse field of ~ 20 mV/m and $v_{oz} \sim 25$ km/sec could result in the wave excitation. Larger transverse electric fields and/or larger parallel currents can

result into excitation of modes with higher k_z/k_y . We note that the Harang discontinuity observations of Sofko et al. [1985] show a transition from near ion-acoustic to subcritical (type III - like) velocities, and then back to near ion-acoustic velocity in the period of less than 2 minutes (See Fig. 6. of Sofko et al. [1985]). These observations are in agreement with the above ideas of a short-lived parallel current influencing the auroral electrojet instabilities. We find from the above estimates that in general the linear excitation of modes with large $k_z/k_y \sim 0.2$ involves threshold requirements which appear difficult to satisfy, based upon the observed magnitudes of currents. Therefore, we suggest the possibility that the modes that are excited linearly with small k_z saturate nonlinearly by generating modes with larger k_z that are frequently observed. A theory suggesting this effect has recently been proposed [Rosenbluth and Sudan, 1986].

In conclusion, we have suggested here that the field-aligned currents may influence the generation of small-scale plasma irregularities in the auroral electrojet, via the Farley-Buneman and ion-acoustic instabilities. This effect could explain the generation of irregularities that are non-field aligned, or, are generated under the subcritical conditions. These irregularities are detected by the VHF radar, and, usually appear to be colocated with the electrojets. We also note that auroral irregularities have been detected in the regions of the downward Birkeland currents [Tsunoda et al., 1976; McDiarmid and McNamara, 1978]. Large field-aligned currents are usually associated with disturbed geomagnetic conditions, and some of these observations have shown such a correlation. Although, we have not considered any nonlocal effects, considering the small scalesizes ($\lambda_{\perp} \sim 3$ meter, $\lambda_{\parallel} \sim 30 - 300$ meters) of interest, the basic effect of parallel currents modifying the threshold criteria of electrojet current-driven modes should be good to lowest order.

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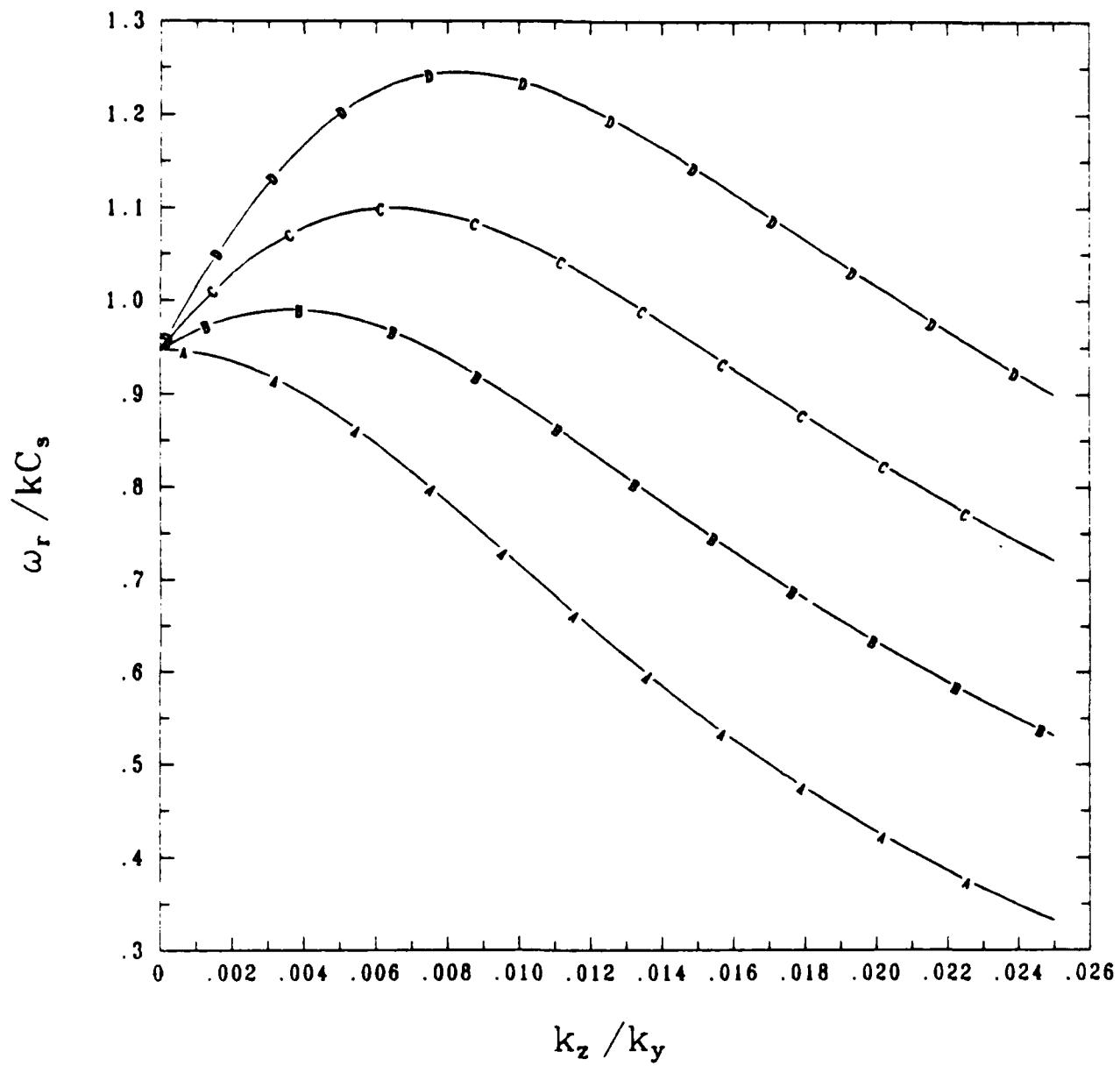


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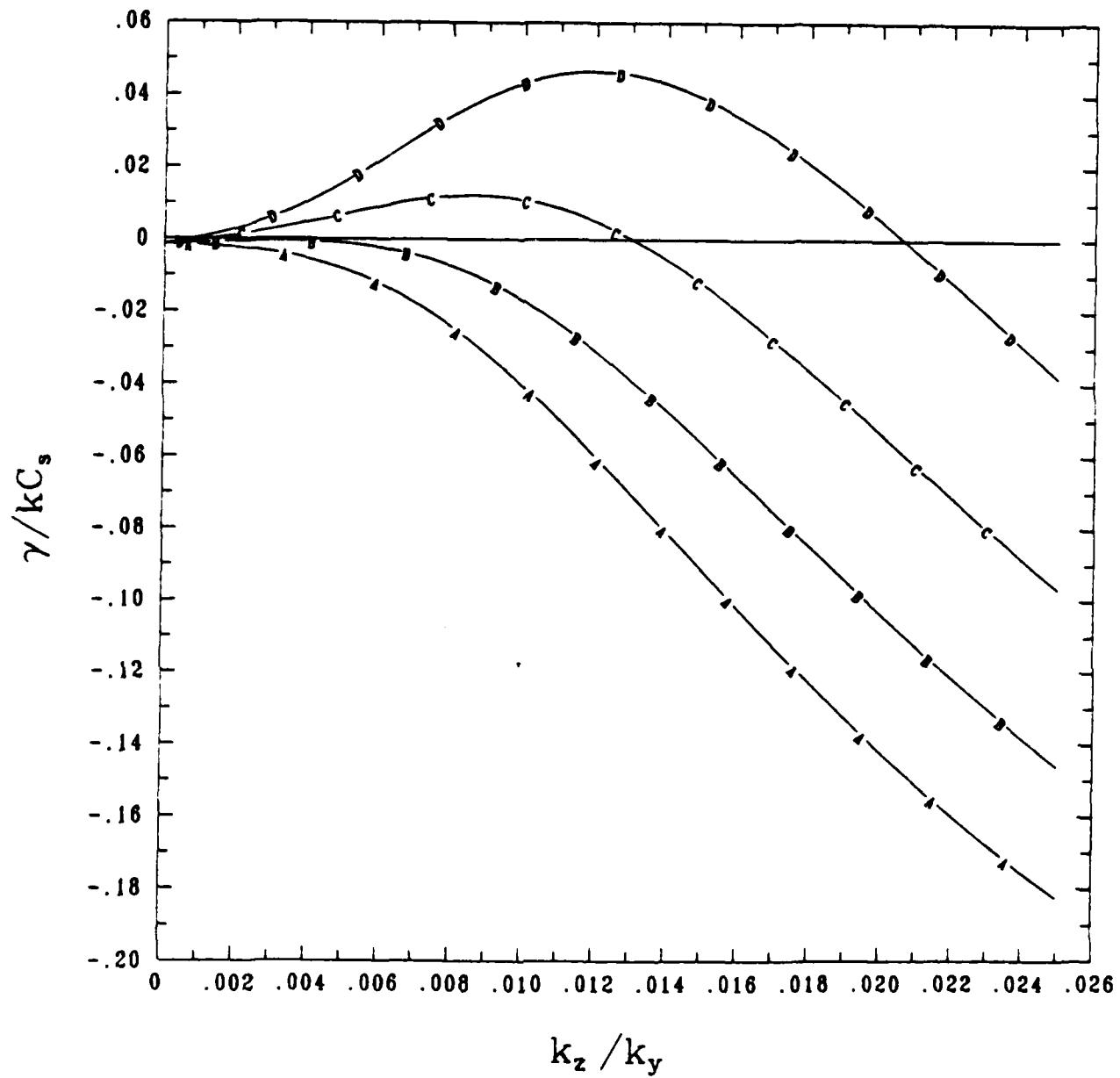


Fig. 1 (Continued) — Plot of $\omega/k_y C_s$ vs k_z/k_y for the parameters $v_{oy}/C_s = 1.0$, $v_{in}/k_y C_s = 3.5$, $v_e/\Omega_e = 4.0 \times 10^{-3}$, $v_i/\Omega_i = 14.0$, and $v_{oz}/C_s = 0, 25, 50$, and 75 (denoted by A, B, C, and D, respectively), and the perpendicular threshold velocity v_{oy}/C_s vs k_y/k_z for the same parameters. (b) The growth rate $\gamma/k_y C_s$ vs k_z/k_y .

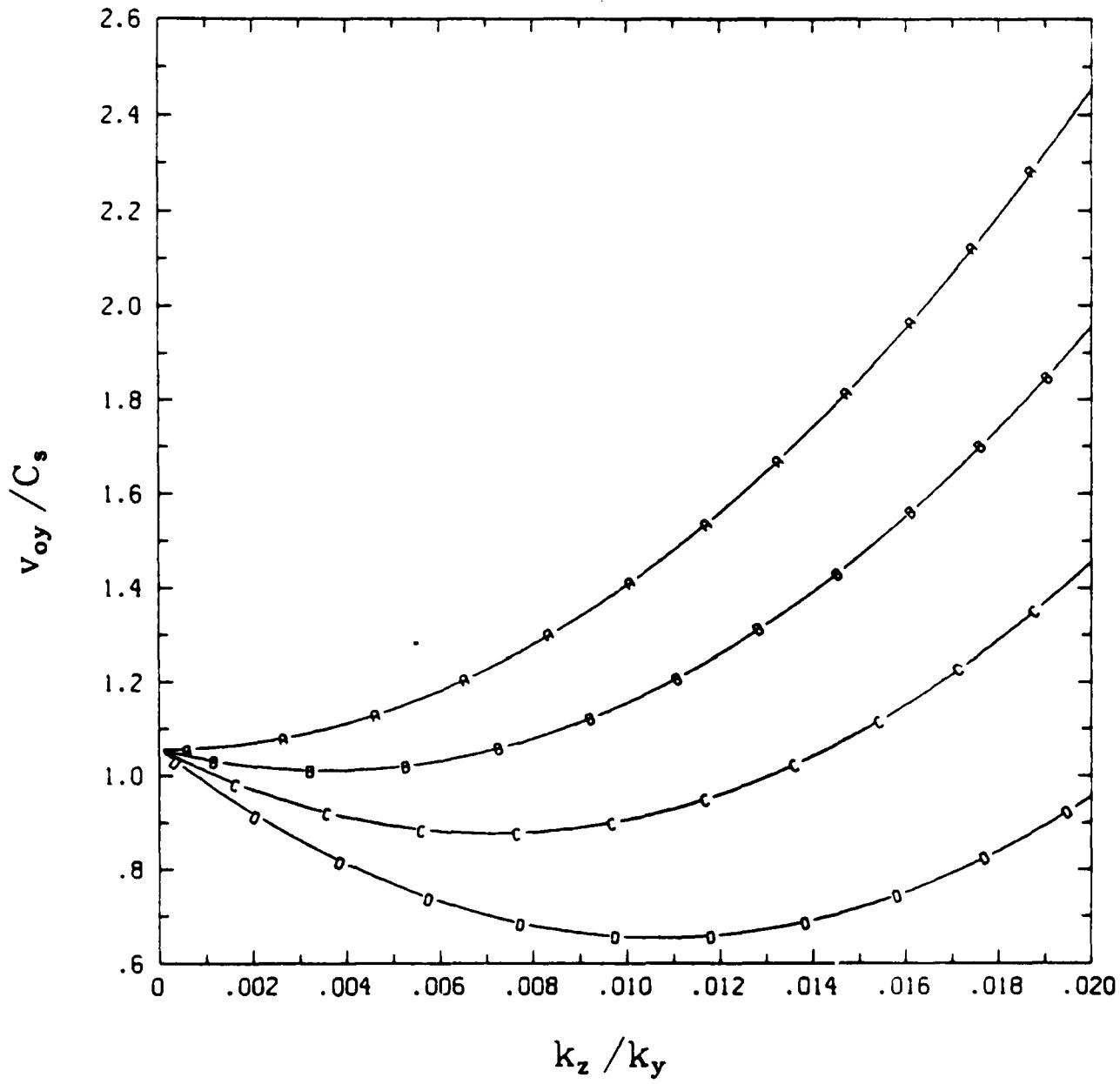


Fig. 1 (Continued) — Plot of $\omega/k_y C_s$ vs k_z/k_y for the parameters $v_{oy}/C_s = 1.0$, $v_{in}/k_y C_s = 3.5$, $v_e/\Omega_e = 4.0 \times 10^{-3}$, $v_i/\Omega_i = 14.0$, and $v_{oz}/C_s = 0, 25, 50$, and 75 (denoted by A, B, C, and D, respectively), and the perpendicular threshold velocity v_{oy}/C_s vs k_y/k_z for the same parameters. (c) The perpendicular threshold velocity v_{oy}/C_s vs k_z/k_y .

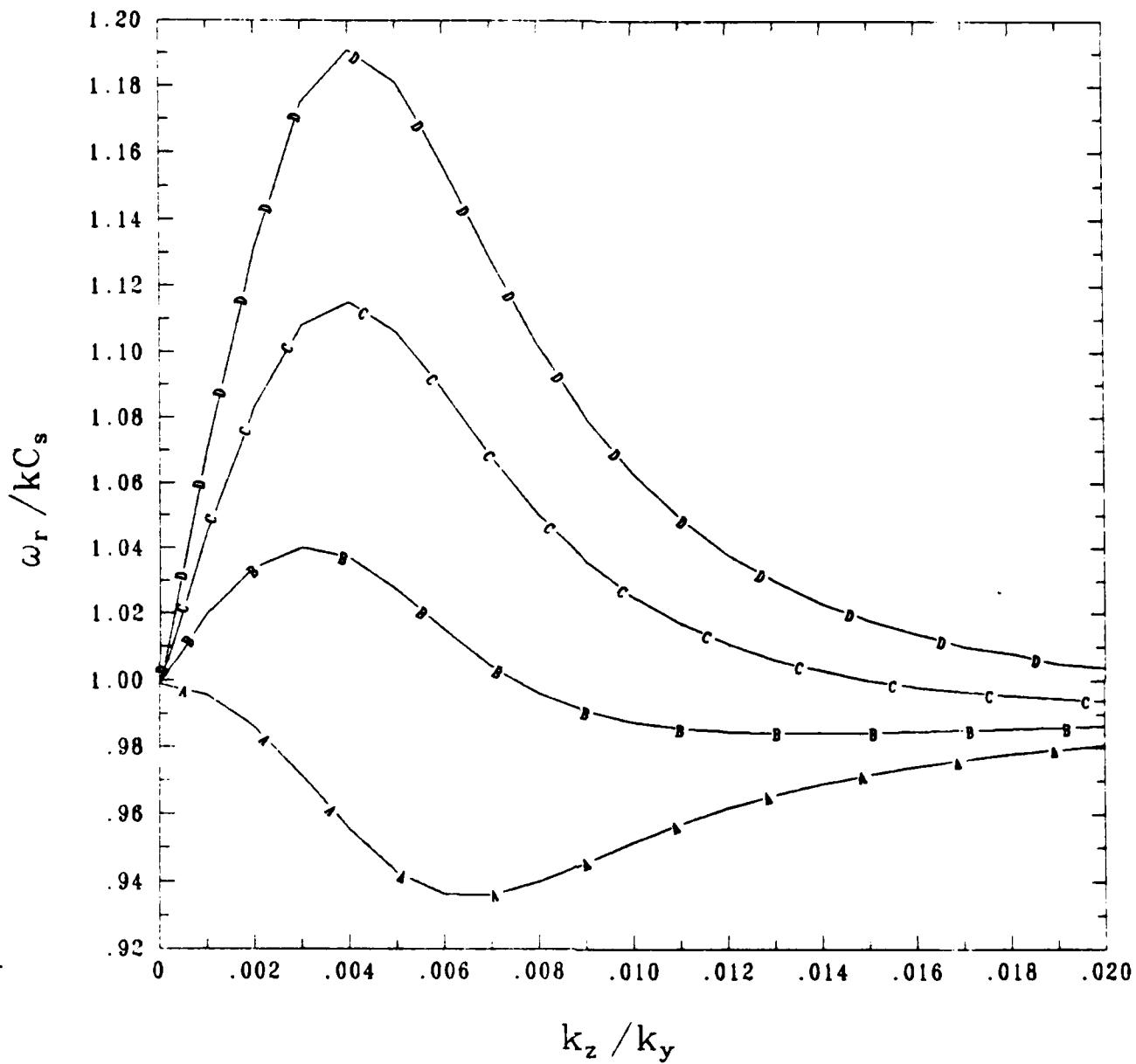


Fig. 2 — Plot of $\omega/k_y C_s$ vs k_z/k_y for the parameters $v_{oy}/C_s = 1.0$, $v_{in}/k_y C_s = 0.25$, $v_e/\Omega_e = 6.0 \times 10^{-4}$, $v_{in}/\Omega_i = 2.0$, and $v_{oz}/C_s = 0, 25, 50$, and 75 (denoted by A, B, C, and D, respectively). (a) The real frequency $\omega_r/k_y C_s$ vs k_z/k_y .

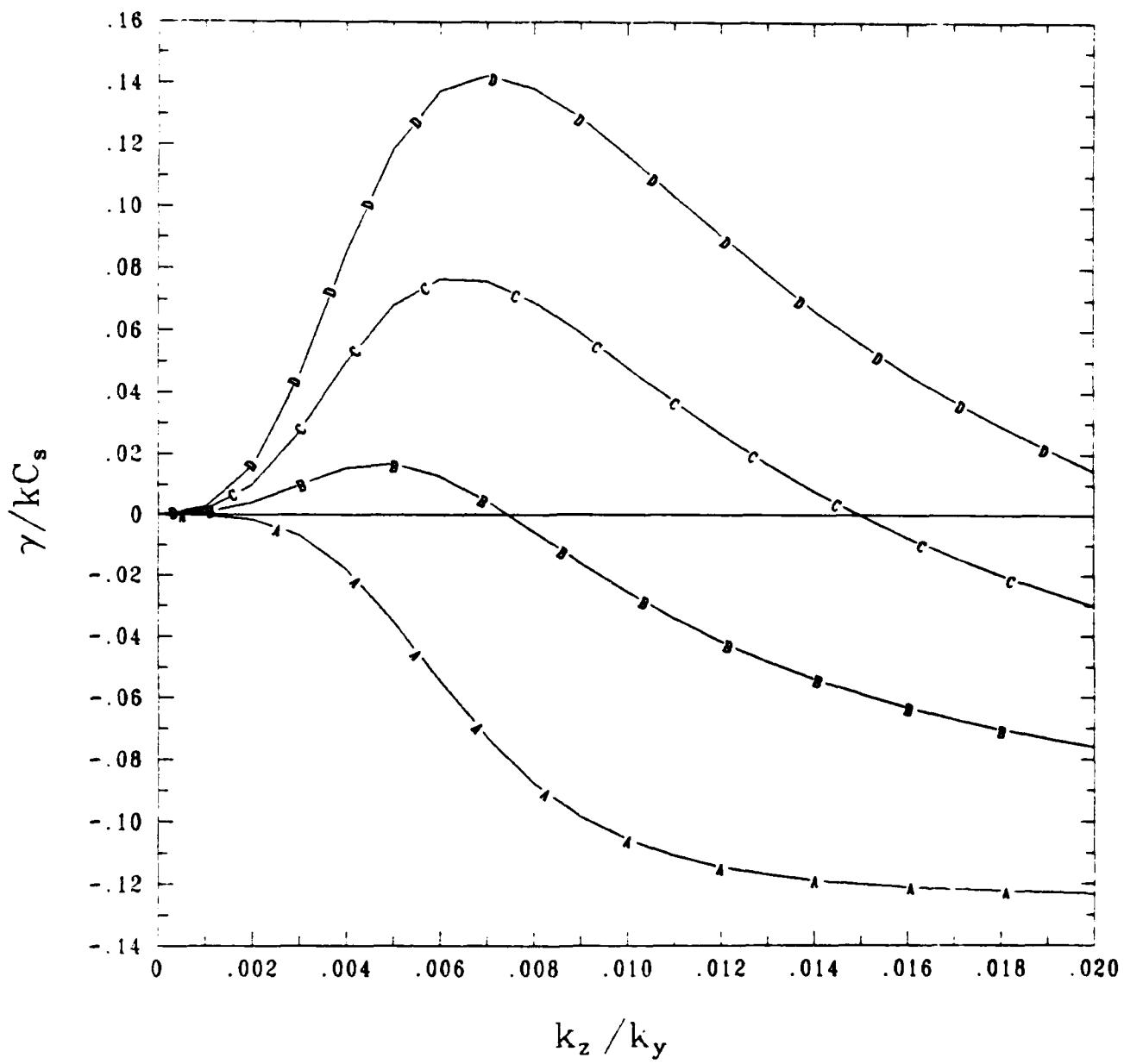


Fig. 2 (Continued) — Plot of $\omega/k_y C_s$ vs k_z/k_y for the parameters $v_{oy}/C_s = 1.0$, $v_{in}/k_y C_s = 0.25$, $\nu_e/\Omega_e = 6.0 \times 10^{-4}$, $\nu_{in}/\Omega_i = 2.0$, and $v_{oz}/C_s = 0, 25, 50$, and 75 (denoted by A, B, C, and D, respectively). (b) The growth rate $\gamma/k_y C_s$ vs k_z/k_y .

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